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## (54) METHOD AND APPARATUS FOR DETERMINING THE NATURE OF SUBTERRANEAN RESERVOIRS

METHODE UND APPARAT ZUR BESTIMMUNG DER NATUR EINES UNTERIRDISCHEN RESERVOIRS

PROCEDE ET APPAREIL PERMETTANT DE DETERMINER LA NATURE DES RESERVOIRS SOUTERRAINS

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(56) References cited:
**WO-A-00/54075**
**WO-A-01/57555**
**US-A- 2 077 707**
**US-A- 4 047 098**
**US-A- 4 258 321**
**US-A- 4 617 518**
**US-A- 5 400 030**





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## Description

**[0001]** The present invention relates to a method and apparatus for determining the nature of submarine and subterranean reservoirs. The invention is particularly suitable for determining whether a reservoir, whose approximate geometry and location are known, contains hydrocarbons or water, though it can also be applied to detecting reservoirs with particular characteristics.

**[0002]** Currently, the most widely used techniques for geological surveying, particularly in submarine situations, are seismic methods. These seismic techniques are capable of revealing the structure of the subterranean strata with some accuracy. However, whereas a seismic survey can reveal the location and shape of a potential reservoir, it cannot reveal the nature of the reservoir.

**[0003]** The solution therefore is to drill a borehole into the reservoir. However, the costs involved in drilling an exploration well tend to be in the region of £25m and since the success rate is generally about 1 in 10, this tends to be a very costly exercise.

**[0004]** It is therefore an object of the invention to provide a system for determining, with greater certainty, the nature of a subterranean reservoir without the need to sink a borehole.

**[0005]** It has been appreciated by the present applicants that while the seismic properties of oil-filled strata and water-filled strata do not differ significantly, their electromagnetic resistivities (permittivities) do differ. Thus, by using an electromagnetic surveying method, these differences can be exploited and the success rate in predicting the nature of a reservoir can be increased significantly. This represents potentially an enormous cost saving.

**[0006]** Consequently, a method and apparatus embodying these principles from the basis of the present applicant's co-pending International patent application PCT/GB01/00419.

**[0007]** This contemplates a method of determining the nature of a subterranean reservoir whose approximate geometry and location are known, which comprises: applying a time varying electromagnetic field to the strata containing the reservoir; detecting the electromagnetic wave field response; seeking in the wave field response, a component representing a refracted wave from the hydrocarbon layer; and determining the content of the reservoir, based on the presence or absence of a wave component refracted by the hydrocarbon layer.

**[0008]** It also contemplates a method for searching for a hydrocarbon containing subterranean reservoir which comprises: applying a time varying electromagnetic field to subterranean strata; detecting the electromagnetic wave field response; seeking, in the wave field response, a component representing a refracted wave; and determining the presence and/or nature of any reservoir identified based on the presence or absence of a wave component refracted by hydrocarbon layer.

**[0009]** It further contemplates an apparatus for determining the nature of a subterranean reservoir whose approximate geometry and location are known, or for searching for a hydrocarbon containing subterranean reservoir, the apparatus comprising: means for applying a time varying electromagnetic field to the strata containing the reservoir; means for detecting the electromagnetic wave field response; and means for seeking, in the wave field response, a component representing a refracted wave, thereby enabling the presence and/or nature of a reservoir to be determined.

**[0010]** A refracted wave behaves differently, depending on the nature of the stratum in which it is propagated. In particular, the propagation losses in hydrocarbon stratum are much lower than in a water-bearing stratum while the speed of propagation is much higher. Thus, when an oil-bearing reservoir is present, and an EM field is applied, a strong and rapidly propagated refracted wave can be detected. This may therefore indicate the presence of the reservoir or its nature if its presence is already known.

**[0011]** Electromagnetic surveying techniques in themselves are known see for example patent publication US 2,077,707, US 4,617,518 or US 4,258,321. However, they are not widely used in practice. In general, the reservoirs of interest are about 1 km or more below the seabed. In order to carry out electromagnetic surveying as a stand alone technique in these conditions, with any reasonable degree of resolution, short wavelengths are necessary. Unfortunately, such short wavelengths suffer from very high attenuation. Long wavelengths do not provide adequate resolution. For these reasons, seismic techniques are preferred.

**[0012]** However, while longer wavelengths applied by electromagnetic techniques cannot provide sufficient information to provide an accurate indication of the boundaries of the various strata, if the geological structure is already known, they can be used to determine the nature of a particular identified formation, if the possibilities for the nature of that formation have significantly differing electromagnetic characteristics. The resolution is not particularly important and so longer wavelengths which do not suffer from excessive attenuation can be employed.

**[0013]** The resistivity of seawater is about 0.3 ohm-m and that of the overburden beneath the seabed would typically be from 0.3 to 4 ohm-m, for example about 2 ohm-m. However, the resistivity of an oil reservoir is likely to be about 20-300 ohm-m. This large difference can be exploited using the techniques of the present invention.

**[0014]** Typically, the resistivity of a hydrocarbon-bearing formation will be 20 to 300 times greater than water-bearing formation.

**[0015]** Due to the different electromagnetic properties of a gas/oil bearing formation and a water bearing formation, one can expect a reflection and refraction of the transmitted field at the boundary of a gas/oil bearing for-

mation. However, the similarity between the properties of the overburden and a reservoir containing water means that no reflection or refraction is likely to occur.

**[0016]** Thus, an electric dipole transmitter antenna on or close to the sea floor induces electromagnetic (EM) fields and currents in the sea water and in the subsurface strata. In the sea water, the EM-fields are strongly attenuated due to the high conductivity in the saline environment, whereas the subsurface strata with less conductivity potentially can act as a guide for the EM-fields (less attenuation). If the frequency is low enough (in the order of 1 Hz), the EM-waves are able to penetrate deep into the subsurface, and deeply buried geological layers having higher electrical resistivity than the overburden (as e.g. a hydrocarbon filled reservoir) will affect the EM-waves. Depending on the angle of incidence and state of polarisation, an EM wave incident upon a high resistive layer may excite a ducted (guided) wave mode in the layer. The ducted mode is propagated laterally along the layer and leaks energy back to the overburden and receivers positioned on the sea floor. The term "refracted" wave in this specification is intended to refer to this wave mode.

**[0017]** Both theory and laboratory experiments show that the ducted mode is excited only for an incident wave with transverse magnetic (TM) polarisation (magnetic field perpendicular to the plane of incidence) and at angles of incidence close to the Brewster angle and the critical angle (the angle of total reflection). For transverse electric (TE) polarisation (electric field perpendicular to the plane of incidence) the ducted mode will not be excited. Since the induced current is proportional to the electric field, the current will be parallel to the layer interfaces for TE polarisation but, for TM polarisation, there is an appreciable current across the layer interfaces.

**[0018]** A horizontal dipole source on the sea floor will generate both TE and TM waves, but by varying the orientation of the receiver antennae, it is possible to vary the sensitivity to the two modes of polarisation. It appears that an in-line orientation (source and receiver dipoles in-line) is more sensitive to the TM mode of polarisation, whereas a parallel orientation (source and receiver dipoles in parallel) is more sensitive to the TE mode of polarisation. The TM mode is influenced by the presence of buried high resistive layers, whereas the TE mode is not. By measuring with the two antenna configurations and exploiting the difference between the two sets of measurements, it is possible to identify deeply buried high resistivity zones, i.e. a hydrocarbon reservoir.

**[0019]** US 4,258,321 is concerned with geophysical surveying using radio waves. The relative magnitude and phase of radio frequency signal components reflected from subterranean formations are measured at several positions along a survey path. At each position, data is taken for the alignment of electric and magnetic vector fields.

**[0020]** The present invention has arisen from this realisation and comprises methods as set forth in the independent claims 1 and 2. According to one aspect of the present invention, there is provided, a method of determining the nature of a subterranean reservoir which comprises: deploying an electric dipole transmitter antenna with its axis generally horizontal; deploying an electric dipole receiver antenna in-line with the transmitter; applying an electromagnetic (EM) field to the strata containing the reservoir using the transmitter; detecting the EM wave field response using the receiver and identifying in the response a component representing a ducted wave from the reservoir according to a first mode; deploying an electric dipole receiver antenna parallel to the transmitter; applying an EM field to the strata using the transmitter; detecting the EM wave field response using the receiver and identifying in the response a component representing a ducted wave from the reservoir according to a second mode; and comparing the first mode ducted wave response with the second mode ducted wave response in order to determine the nature of the reservoir.

**[0021]** According to another aspect of the present invention there is provided, a method of searching for a hydrocarbon-containing subterranean reservoir which comprises: deploying an electric dipole transmitter antenna with its axis generally horizontal; deploying an electric dipole receiver antenna in-line with the transmitter; applying an EM field to subterranean strata using the transmitter; detecting the EM wave field response using the receiver; seeking in the response a component representing a ducted wave according to a first mode, caused by a high-resistivity zone; deploying an electric dipole receiver antenna parallel to the transmitter; applying an EM field to the strata using the transmitter; detecting the EM wave field response using the receiver; seeking in the response a component representing a ducted wave according to a second mode; and comparing the first mode ducted wave response with the second mode ducted wave response in order to determine the presence and/or nature of any high-resistivity zone.

**[0022]** The first mode may be considered to be a TM mode, and the second mode a TE mode.

**[0023]** Thus, according to the invention, measurements are taken with the transmitter and receiver both in-line and parallel, and the two sets of measurements are compared. A characteristic difference in values indicates a highly resistive layer located beneath highly conductive strata. High resistivity indicates the presence of hydrocarbons and so the difference in values is a direct hydrocarbon indicator.

**[0024]** This technique can be used in conjunction with conventional seismic techniques to identify hydrocarbon reservoirs.

**[0025]** Preferably, the transmitter and/or receiver comprises an array of dipole antennae.

**[0026]** The technique is applicable in exploring land-

based subterranean reservoirs but is especially applicable to submarine, in particular sub-sea, subterranean reservoirs. Preferably the field is applied using one or more transmitters located on the earth's surface, and the detection is carried out by one or more receivers located on the earth's surface. In a preferred application, the transmitter(s) and/or receivers are located on or close to the seabed or the bed of some other area of water.

**[0027]** In a preferred arrangement, the transmitter and receiver antennae are located on a common cable towed behind a vessel. This will result in a fixed offset or a series of fixed offsets where several receivers are employed. Preferably, the transmitter transmits both modes and may therefore comprise two dipoles arranged mutually at right angles. Preferably each receiver comprises two dipoles mutually at right angles. Preferably one transmitter dipole and one receiver dipole are arranged at right angles to the direction of the cable. Alternatively the transmitter and/or receivers may each comprise a single dipole antenna arranged obliquely, eg. at 45° to the direction of the cable. With this arrangement the transmitted field is resolved.

**[0028]** Using this technique, it is possible to achieve comparable results from the two modes as the same signal and offset are used. It will not matter greatly if the transmitter drifts in frequency or amplitude. Furthermore, reservoirs can be detected in real time. Thus, if the results show a difference in the two modes, this will strongly indicate the presence of an H/C bearing reservoir and so a more detailed study can be made at once.

**[0029]** Such a system would generally use a single transmission source and several receivers, typically more than ten. The different offsets would be suitable for detecting reservoirs at different depths.

**[0030]** The receivers can be deployed on a single cable or on a series of parallel cables. There may also be several transmitters.

**[0031]** In practice, the vessel would normally stop and the cable allowed to sink prior to transmission. There would be a transmission at several different frequencies before moving to another location. The technique is particularly suitable for edge detection, and it is a simple matter to select a suitable resolution. However, if the surveying is being carried out in an undetermined area, the resistivity in the top layers should be mapped, for example with MT methods or by inversion after a reflection study.

**[0032]** If the offset between the transmitter and receiver is significantly greater than three times the depth of the reservoir from the seabed (i.e. the thickness of the overburden), it will be appreciated that the attenuation of the refracted wave will often be less than that of direct wave and the reflected wave. The reason for this is the fact that the path of the refracted wave will be effectively distance from the transmitter down to the reservoir i.e. the thickness of the overburden, plus the offset along the reservoir, plus the distance from the reservoir up to the receivers i.e. once again the thickness of the overburden.

**[0033]** The polarization of the source transmission will determine how much energy is transmitted into the oil-bearing layer in the direction of the receiver. A dipole antenna is therefore the selected transmitter. In general, it is preferable to adopt a dipole with a large effective length. The transmitter dipole may therefore be 100 to 1000 meters in length and may be towed in two orthogonal directions. The receiver dipole optimum length is determined by the thickness of the overburden.

**[0034]** The transmitted field may be pulsed, however, a coherent continuous wave with stepped frequencies is preferred. It may be transmitted for a significant period of time, during which the transmitter should preferably be stationary (although it could be moving slowly), and the transmission stable. Thus, the field may be transmitted for a period of time from 3 seconds to 60 minutes, preferably from 3 to 30 minutes, for example about 20 minutes. The receivers may also be arranged to detect a direct wave and a wave refracted from the reservoir, and the analysis may include extracting phase and amplitude data of the refracted wave from corresponding data from the direct wave.

**[0035]** Preferably, the wavelength of the transmission should be in the range

$$0.1s \leq \lambda \leq 5s;$$

where $\lambda$ is the wavelength of the transmission through the overburden and s is the distance from the seabed to the reservoir. More preferably $\lambda$ is from about 0.5s to 2s. The transmission frequency may be from 0.01 Hz to I kHz, preferably from 1 to 20 Hz, for example 5 Hz.

**[0036]** Preferably, the distance between the transmitter and a receiver should be in the range

$$0.5\,\lambda \leq L \leq 10\,\lambda;$$

where $\lambda$ is the wavelength of the transmission through the overburden and L is the distance between the transmitter and the first receiver.

**[0037]** It will be appreciated that the present invention may be used to determine the position, the extent, the nature and the volume of a particular stratum, and may also be used to detect changes in these parameters over a period of time.

**[0038]** The present invention also extends to a method of surveying subterranean measures which comprises; performing a seismic survey to determine the geological structure of a region; and where that survey reveals the presence of a subterranean reservoir, subsequently performing a method as described above.

**[0039]** The invention may be carried into practice in various ways and will now be illustrated in the following embodiments and reduced scale investigations and

simulations. In the accompanying drawings,

Figure 1 is a vertical cross-section through a testing tank;

Figure 2 is a plan view of the tank of Figure 1;

Figure 3 is a plan view of the antennae used in the tank of Figure 1;

Figure 4 is a side view of the antenna in Figure 3;

Figures 5 and 6 are respectively a schematic plan view and side view of the testing tank set up for measurement;

Figures 7 is a graph showing calculated and measured values for the transmitted electric field for a given frequency in the model experiment;

Figure 8 is a graph showing calculated values for the electric field in a realistic earth model;

Figure 9 is a schematic side view of a cable layout towed by a vessel;

Figure 10 is a plan view corresponding to Figure 9; and

Figures 11 and 12 are views similar to Figure 10 showing two alternative arrangements.

**[0040]** The tank 11 shown in Figure 1 and 2 comprises a concrete enclosure 9m long, 6m wide and 8m in depth. The tank 11 is filled with sea water 12. A diaphragm 13 filled with fresh water 14 is located in the tank. The diaphragm 13 is 7.5m long, 4.25m wide and 0.25m thick and can be located at any desired height in a horizontal orientation within the tank 11.

**[0041]** The conductivity of the sea water 12 was measured to be 5.3 S/m at 14°C and the conductivity of the fresh water was measured to be 0.013 S/m. The ratio of the two conductivities is therefore very close to 400.

**[0042]** The critical frequency $f_c$ of a conducting medium, i.e. the frequency at which the displacement current is equal to the conduction current, is given by

$$f_c = \frac{\sigma}{2\pi\varepsilon_r\varepsilon_0} \approx 18 \cdot \frac{\sigma}{\varepsilon_r} \ GHz$$

where $\varepsilon_r$ is the relative dielectric constant of the medium, and $\sigma$ the conductivity in S/m. For water, $\varepsilon_r = 80$ at the frequencies and temperatures of interest. For the two conductivity values $\sigma = 5.2$ S/m and $\sigma = 0.013$ S/m, $f_c$ = 1.2 GHz and 3 Mhz, respectively. Since, in the experiments, the highest frequency is 0.83 MHz, it is a fair approximation to neglect the displacement current, even for the fresh water.

**[0043]** For a non magnetic, conductive medium, the propagation constant $\gamma$ is given by

$$\gamma = j\omega\sqrt{\varepsilon\mu} = j\omega\sqrt{\left(\varepsilon_r\varepsilon_0 + \frac{\sigma}{j\omega}\right)\mu_0}$$

$$\approx \sqrt{j\omega\mu_0\sigma} = 2\pi\sqrt{\frac{j \cdot f\sigma}{5}}$$

**[0044]** The wavelength $\lambda$, defined as the distance in which the phase changes $2\pi$, is given by

$$\lambda = \frac{2\pi}{\mathrm{Re}\{\gamma\}} \approx \sqrt{\frac{10}{f\sigma}}$$

$\lambda$ m, $f$ in MHz and $\sigma$ in S/m. The skin depth, the distance in which the amplitude diminishes by 1/e, is related to the wavelength by

$$\delta = \frac{\lambda}{2\pi} = \sqrt{\frac{\pi}{2f\mu_0\sigma}}$$

**[0045]** For the extremes of the frequency range, for the sea water with $\sigma$=5.2 S/m,

| Frequency | 30 kHz | 830 kHz |
|---|---|---|
| Skin depth<br>Wavelength | 1.27 m<br>8.01 m | 0.24 m<br>1.52 m |

and for the fresh water with $\sigma$ = 0.013 S/m,

| Frequency | 30 kHz | 830 kHz |
|---|---|---|
| Skin depth<br>Wavelength | 25.4 m<br>160.2 m | 4.8 m<br>30.4 m |

**[0046]** Referring now to Figures 3 and 4, two identical electrical dipole antennae, as shown were used for the transmitter and receiver.

**[0047]** Each antenna 15 comprises two square brass plates 16, 15cm square, mounted on an epoxy substrate 17. Each plate 16 is connected to a co-axial cable 18, which passes through an epoxy tube 19 mounted at right angles to the plate 16, to a balun which transforms the impedance of the antenna 15 from about 2Ω in sea water to about 50Ω.

**[0048]** The measurement set-up is shown in Figure 5 and 6. An automatic network analyser (ANA) measures

the transmission between the antennae 15 as a function of distance (offset) and frequency. The arrangement shown in Figure 5 shows the antennae 15 in the parallel orientation. The in-line orientation is achieved by rotating both antennae through 90° in the horizontal plane.

**[0049]** The results of the measurements are shown in Figure 7 together with the corresponding theoretical results. The measurements agree well with the theoretical results and the figure contains two sets of curves, one with parallel antennae and one with the antennae in line. The theoretical results are computed for infinitesimal dipole antennae. The orientations of the antennae and the frequency are shown on the Figures.

**[0050]** The parameters of the experiment are scaled relative to possible practical situations.

To give an idea of orders of magnitude; if the frequency is scaled down by a factor of 40,000 and the conductivity by a factor of 10, the dimensions will be scaled up by a factor of 632, and the experimental setup would correspond to a low conductivity layer of thickness 150 m and conductivity 0.0013 S/m below an overburden of thickness 300 m and conductivity 0.52 S/m. The corresponding frequency range would be from 0.75 Hz to 20 Hz, and the length of the antenna nearly 300 m.

**[0051]** The method with the TE and TM-mode have been tested by computer simulations on a simple horizontally layered earth model with electrical parameter values for typical deep water subsurface sediments. The model has an infinite insulating air layer, a 1150 meter water layer of $0.3125\Omega m$, 950 meter overburden of $1\Omega m$, a 150 meter reservoir zone of $50\Omega m$ and an infinite underburden of $1\Omega m$. Figure 8 illustrates the amplitude response |E| (electric field) as a function of receiver offset, caused by a 1 Hz signal. Responses from both the TM-mode (solid with x's) and TE-mode (dashed with +'s) are shown. The amplitudes for the TM-mode are approximately 10 times larger at an offset of 5 km. As a reference, the response from a homogenous half-space of $1\Omega m$ is shown for both configurations (corresponding to a response from a water filler reservoir or outside the reservoir area). The TE-mode has the largest deviation from its half-space, ie. this mode is more sensitive to a hydrocarbon layer.

**[0052]** Figures 9 and 10 show a vessel 31 towing a cable (or streamer) 32 just above the seabed 33. The cable 32 carries a transmitter dipole antenna 34 and several receiver dipoles 35, only four of which are shown. The depth of water might be of the order of 1000m, the offset between the transmitter 34 and the nearest receiver 35 might be about 2000m and the receivers might be about 100m apart. The transmitter 34 is controlled from the vessel 31 via the cable 32 and the responses detected by the receivers 35 are relayed back to the vessel 31 in real time, again via the cable 32.

**[0053]** Figure 10 shows an arrangement in which the vessel 31 tows three cables 41, 42, 43, each carrying a series of receivers 45, 46, 47. The spacing of the three cables 41, 42, 43 is achieved by means of a spar 44.

**[0054]** In the arrangement shown in Figure 11, the transmitter 48 is in the form of two dipole antennae, one parallel to the cable 42 and one at right angles.

**[0055]** The arrangement shown in Figure 12 is similar to Figure 11, but in this case, the transmitter 51 is a single dipole antenna arranged at 45° to the cable 42.

## Claims

1. A method of determining the nature of a subterranean reservoir which comprises deploying an electric dipole transmitter antenna (34) with its axis generally horizontal, deploying an electric dipole receiver antenna (35) in-line with the transmitter (34), applying an electromagnetic (EM) field to the strata containing the reservoir using the transmitter and detecting the EM wave field response using the receiver **characterised by**: identifying in the response a component representing a ducted wave from the reservoir according to a first mode; deploying an electric dipole receiver antenna (35) parallel to the transmitter; applying an EM field to the strata using the transmitter; detecting the EM wave field response using the receiver and identifying in the response a component representing a ducted wave from the reservoir according to a second mode; and comparing the first mode ducted wave response with the second mode ducted wave response in order to determine the nature of the reservoir.

2. A method of searching for a hydrocarbon-containing subterranean reservoir which comprises deploying an electric dipole transmitter antenna (34) with its axis generally horizontal, deploying an electric dipole receiver antenna (35) in-line with the transmitter, applying an EM field to subterranean strata using the transmitter and detecting the EM wave field response using the receiver **characterised by**: seeking in the response a component representing a ducted wave according to a first mode, caused by a high-resistivity zone; deploying an electric dipole receiver antenna (35) parallel to the transmitter; applying an EM field to the strata using the transmitter; detecting the EM wave field response using the receiver; seeking in the response a component representing a ducted wave according to a second mode; and comparing the first mode ducted wave response with the second mode ducted wave response in order to determine the presence and/or nature of any high-resistivity zone.

3. A method as claimed in Claim 1 or Claim 2, **characterised in that** the first mode is a TM mode of polarisation and/or the second mode is a TE mode of polarisation.

4. A method as claimed in any preceding Claim, **char-**

**acterised in that** the transmitter (34) and/or receiver (35) comprises an array of dipole antennae.

5. A method as claimed in any preceding Claim, **characterised in that** the transmitter and/or receiver (34,35) is located on or close to the seabed (33) or the bed of some other area of water.

6. A method as claimed in any preceding Claim, **characterised in that** the transmitter (34) and receivers (35) are located on a common cable (32) arranged to be towed behind a vessel (31).

7. A method as claimed in Claim 6 **characterised in that** the transmitter (51) and/or receiver each comprise two dipole antennae (34,35) arranged mutually at right angles.

8. A method as claimed in any preceding Claim, **characterised in that** the frequency of the EM field is continuously varied over the transmission period.

9. A method as claimed in any preceding Claim, **characterised in that** the field is transmitted for a period of time for 3 seconds to 60 minutes, preferably from 3 to 30 minutes.

10. A method as claimed in any preceding Claim, **characterised in that** the wavelength of the transmission is given by the formula

$$0.1s \leq \lambda \leq 10s;$$

wherein $\lambda$ is the wavelength of the transmission through the overburden and s is the distance from the seabed (33) to the reservoir.

11. A method as claimed in any preceding Claim, **characterised in that** distance between the transmitter and a receiver is given by the formula

$$0.5\ \lambda \leq L \leq 10\ \lambda$$

where $\lambda$ is the wavelength of the transmission through the overburden and L is the distance between the transmitter (34) and the receiver (35).

12. A method as claimed in any of Claims 8 to 11, **characterised in that** the transmission frequency is from 0.01 Hz to 1 kHz, preferably from 1 to 20 Hz.

13. A method as claimed in any preceding Claim, **characterised in that** it includes suppressing the direct wave and/or any other known wave contribution that may disturb the measurements, thereby reducing the required dynamic range of the receiver (35) and increasing the resolution of the refracted wave.

14. A method of surveying subterranean measures which comprises: performing a seismic survey to determine the geological structure of a region and where that survey reveals the presence of a subterranean reservoir, subsequently performing a method as claimed in any preceding Claim.

**Patentansprüche**

1. Verfahren zur Bestimmung der Natur eines unterirdischen Reservoirs, welches Verfahren das Positionieren einer elektrischen Dipol-Sendeantenne (34), wobei deren Achse im Allgemeinen horizontal ist, das Positionieren einer elektrischen Dipol-Empfangsantenne (35) in Reihe mit dem Sender (34), das Anlegen eines elektromagnetischen (EM) Feldes an die das Reservoir enthaltenden Schichten unter Verwendung des Senders, und das Erfassen der EM-Wellenfeldantwort unter Verwendung des Empfängers aufweist, **dadurch gekennzeichnet, dass** in der Antwort eine Komponente identifiziert wird, welche eine geleitete Welle aus dem Reservoir gemäß einem ersten Modus darstellt; dass eine elektrische Dipol-Empfangsantenne (35) parallel zum Sender positioniert wird; dass ein EM-Feld an die Schichten unter Verwendung des Senders angelegt wird; dass die EM-Wellenfeldantwort unter Verwendung des Empfängers erfasst und eine Komponente in der Antwort identifiziert wird, welche eine geleitete Welle aus dem Reservoir gemäß einem zweiten Modus darstellt; und dass die Antwort der geleiteten Welle des ersten Modus mit der Antwort der geleiteten Welle des zweiten Modus verglichen wird, um die Natur des Reservoirs zu bestimmen.

2. Verfahren zum Suchen nach einem kohlenwasserstoffhältigen unterirdischen Reservoir, welches das Positionieren einer elektrischen Dipol-Sendeantenne (34), wobei deren Achse im Allgemeinen horizontal ist, das Positionieren einer elektrischen Dipol-Empfangsantenne (35) in Reihe mit dem Sender, Anlegen eines EM-Feldes an unterirdische Schichten unter Verwendung des Senders und Erfassen der EM-Wellenfeldantwort unter Verwendung des Empfängers aufweist, **dadurch gekennzeichnet, dass** in der Antwort eine Komponente gesucht wird, welche eine durch eine Zone mit hoher Widerstandsfähigkeit hervorgerufene geleitete Welle gemäß einem ersten Modus darstellt; eine elektrische Dipol-Empfängerantenne (35) parallel zum Sender positioniert wird; ein EM-Feld an die Schichten unter Verwendung des Senders angelegt wird; die EM-Wellenfeldantwort unter Verwendung des Empfängers erfasst wird; eine Komponente in

der Antwort gesucht wird, welche eine geleitete Welle gemäß einem zweiten Modus darstellt; und die Antwort der geleiteten Welle des ersten Modus mit der Antwort der geleiteten Welle des zweiten Modus verglichen wird, um die Gegenwart und/oder Natur einer etwaigen Zone mit hoher Widerstandsfähigkeit zu bestimmen.

3. Verfahren nach Anspruch 1 oder 2, **dadurch gekennzeichnet, dass** der erste Modus ein TM-Polarisierungsmodus und/oder der zweite Modus ein TE-Polarisierungsmodus ist.

4. Verfahren nach einem der vorhergehenden Ansprüche, **dadurch gekennzeichnet, dass** der Sender (34) und/oder der Empfänger (35) eine Anordnung von Dipol-Antennen aufweisen.

5. Verfahren nach einem der vorhergehenden Ansprüche, **dadurch gekennzeichnet, dass** der Sender und/oder Empfänger (34, 35) auf dem Meeresboden (33) oder nahe beim Meeresboden (33) oder dem Boden eines anderen Wassergebietes angeordnet wird.

6. Verfahren nach einem der vorhergehenden Ansprüche, **dadurch gekennzeichnet, dass** sich die Sender (34) und die Empfänger (35) an einem gemeinsamen Kabel (32) befinden, das so angeordnet ist, dass es hinter einem Schiff (31) gezogen wird.

7. Verfahren nach Anspruch 6, **dadurch gekennzeichnet, dass** der Sender (51) und/oder Empfänger jeweils zwei Dipol-Antennen (34, 35) aufweisen, die zueinander in rechten Winkeln angeordnet sind.

8. Verfahren nach einem der vorhergehenden Ansprüche, **dadurch gekennzeichnet, dass** die Frequenz des EM-Feldes über die Sendezeit hinweg kontinuierlich verändert wird.

9. Verfahren nach einem der vorhergehenden Ansprüche, **dadurch gekennzeichnet, dass** das Feld über einen Zeitraum von 3 Sekunden bis 60 Minuten, vorzugsweise von 3 bis 30 Minuten gesendet wird.

10. Verfahren nach einem der vorhergehenden Ansprüche, **dadurch gekennzeichnet, dass** die Sendewellenlänge durch die Formel

$$0{,}1\ s \leq \lambda \leq 10\ s$$

gegeben ist, wobei $\lambda$ die Sendewellenlänge durch die Überlast hindurch und s die Entfernung vom Meeresboden (33) zum Reservoir ist.

11. Verfahren nach einem der vorhergehenden Ansprüche, **dadurch gekennzeichnet, dass** die Entfernung zwischen dem Sender und einem Empfänger durch die Formel

$$0{,}5\ \lambda \leq L \leq 10\ \lambda$$

gegeben ist, wobei $\lambda$ die Sendewellenlänge durch die Überlast hindurch und L der Abstand zwischen dem Sender (34) und dem Empfänger (35) ist.

12. Verfahren nach einem der Ansprüche 8 bis 11, **dadurch gekennzeichnet, dass** die Sendefrequenz von 0,01 Hz bis 1 kHz, vorzugsweise von 1 bis 20 Hz beträgt.

13. Verfahren nach einem der vorhergehenden Ansprüche, **dadurch gekennzeichnet, dass** es das Unterdrücken der direkten Wellen- und/oder aller anderen Wellenbeiträge einschließt, welche die Messungen stören könnten, wodurch die erforderliche dynamische Bandbreite des Empfängers (35) reduziert und die Auflösung der geleiteten Welle erhöht wird.

14. Verfahren zum Aufnehmen von unterirdischen Messungen, welches das Durchführen einer seismischen Messung aufweist, um die geologische Struktur einer Region zu bestimmen, und, falls diese Messung die Gegenwart eines unterirdischen Reservoirs offenbart, anschließendes Durchführen eines Verfahrens nach einem der vorhergehenden Ansprüche.

**Revendications**

1. Procédé pour déterminer la nature d'un réservoir souterrain qui comprend le fait de déployer une antenne émettrice dipôle électrique (34) avec son axe généralement horizontal, déployer une antenne réceptrice dipôle électrique (35) en ligne avec l'émetteur (34), appliquer un champ électromagnétique (EM) aux couches contenant le réservoir en utilisant l'émetteur et détecter la réponse de champ d'ondes EM en utilisant le récepteur, **caractérisé par** : identifier dans la réponse une composante représentant une onde guidée venant du réservoir, selon un premier mode; déployer une antenne réceptrice dipôle électrique (35) parallèle à l'émetteur ; appliquer un champ EM aux couches en utilisant l'émetteur ; détecter la réponse de champ d'ondes EM en utilisant le récepteur et identifier dans la réponse une composante représentant une onde guidée venant du réservoir, selon un second mode; et comparer la réponse d'onde guidée de premier mode avec la ré-

ponse d'onde guidée de second mode pour déterminer la nature du réservoir.

**2.** Procédé pour rechercher un réservoir souterrain contenant des hydrocarbures, qui comprend le fait de déployer une antenne émettrice dipôle électrique (34) avec son axe généralement horizontal, déployer une antenne réceptrice dipôle électrique (35) en ligne avec l'émetteur, appliquer un champ EM aux couches souterraines en utilisant l'émetteur et détecter la réponse de champ d'ondes EM en utilisant le récepteur, **caractérisé par** : rechercher dans la réponse une composante représentant une onde guidée selon un premier mode, due à une zone de grande résistivité; déployer une antenne réceptrice dipôle électrique (35) parallèle à l'émetteur ; appliquer un champ EM aux couches en utilisant l'émetteur ; détecter la réponse de champ d'ondes EM en utilisant le récepteur ; rechercher dans la réponse une composante représentant une onde guidée selon un second mode; et comparer la réponse d'onde guidée de premier mode avec la réponse d'onde guidée de second mode pour déterminer la présence et/ou la nature de toute zone de grande résistivité.

**3.** Procédé selon la revendication 1 ou 2, **caractérisé en ce que** le premier mode est un mode transversal magnétique de polarisation et/ou le second mode est un mode transversal électrique de polarisation.

**4.** Procédé selon une quelconque des revendications précédentes, **caractérisé en ce que** l'émetteur (34) et/ou le récepteur (35) comprend un réseau d'antennes dipôles.

**5.** Procédé selon une quelconque des revendications précédentes, **caractérisé en ce que** l'émetteur et/ou le récepteur (34,35) est situé sur ou proche du fond de la mer (33) ou du fond d'une autre zone d'eau.

**6.** Procédé selon une quelconque des revendications précédentes, **caractérisé en ce que** l'émetteur (34) et les récepteurs (35) sont situés sur un câble commun (32), disposé pour être traîné derrière un bateau (31).

**7.** Procédé selon la revendication 6, **caractérisé en ce que** l'émetteur (51) et/ou le récepteur comprennent chacun deux antennes dipôles (34,35) disposées mutuellement à angle droit.

**8.** Procédé selon une quelconque des revendications précédentes, **caractérisé en ce que** la fréquence du champ EM varie de façon continue pendant la période de transmission.

**9.** Procédé selon une quelconque des revendications précédentes, **caractérisé en ce que** le champ est émis pendant une durée de 3 secondes à 60 minutes, de préférence de 3 à 30 minutes.

**10.** Procédé selon une quelconque des revendications précédentes, **caractérisé en ce que** la longueur d'onde de la transmission est donnée par la formule

$$0{,}1s \leq \lambda \leq 10s;$$

où $\lambda$ est la longueur d'onde de la transmission au travers du terrain de couverture et s est la distance du fond de la mer (33) au réservoir.

**11.** Procédé selon une quelconque des revendications précédentes, **caractérisé en ce que** la distance entre l'émetteur et un récepteur est donnée par la formule

$$0{,}5 \leq \lambda \leq 10s;$$

où $\lambda$ est la longueur d'onde de la transmission au travers du terrain de couverture et L est la distance entre l'émetteur (34) et le récepteur (35).

**12.** Procédé selon une quelconque des revendications 8 à 11, **caractérisé en ce que** la fréquence de transmission est de 0,01 Hz à 1 kHz, de préférence de 1 à 20 Hz.

**13.** Procédé selon une quelconque des revendications précédentes, **caractérisé en ce qu'**il comprend la suppression de l'onde directe et/ou de toute autre contribution d'onde connue qui peut perturber les mesures, réduisant de ce fait la plage dynamique requise du récepteur (35) et augmentant la résolution de l'onde réfractée.

**14.** Procédé pour relever des mesures souterraines qui comprend le fait de : réaliser un relevé sismique pour déterminer la structure géologique d'une région et, où ce relevé révèle la présence d'un réservoir souterrain, effectuer de façon subséquente un procédé selon une quelconque des revendications précédentes.

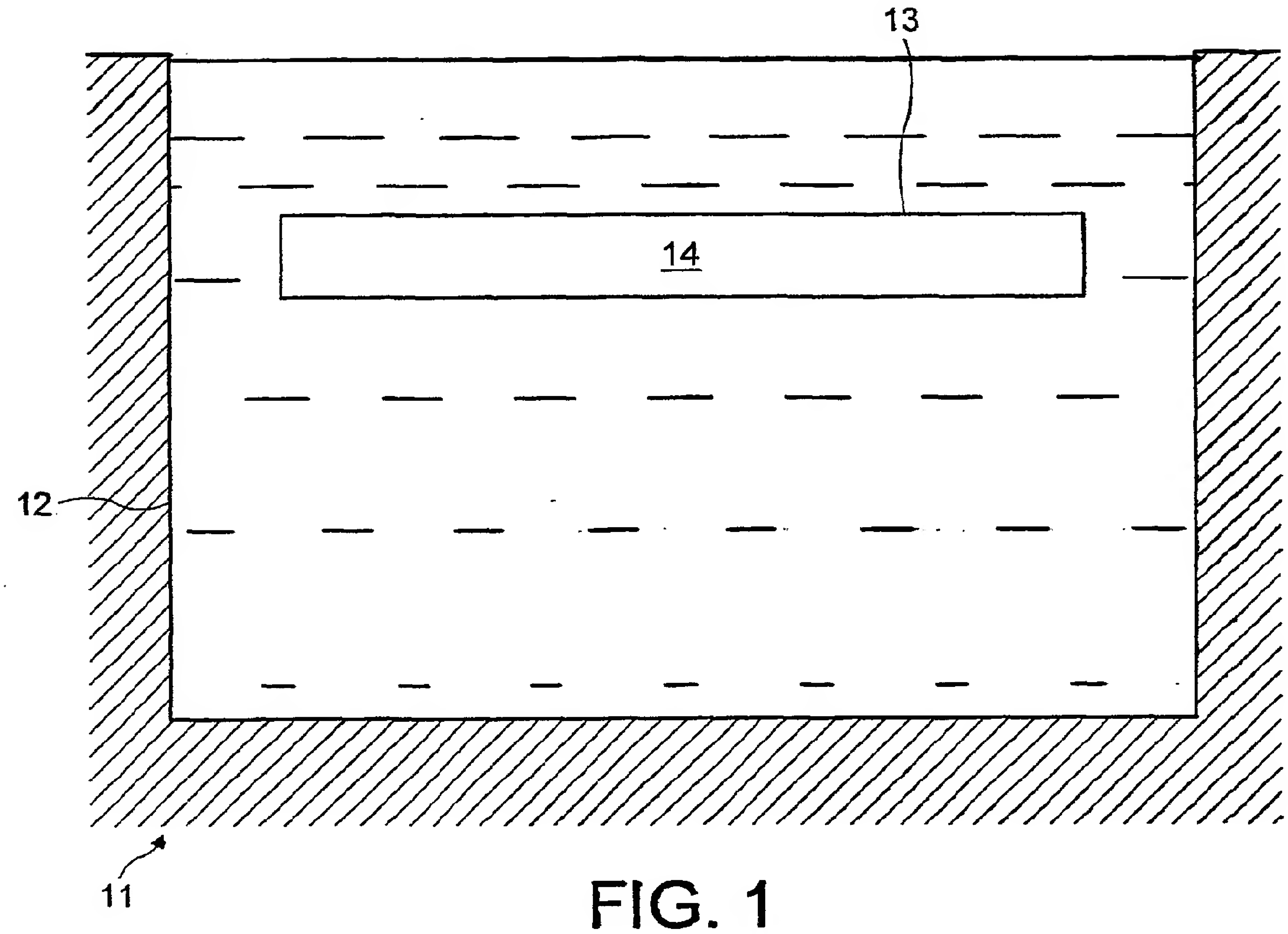



FIG. 1

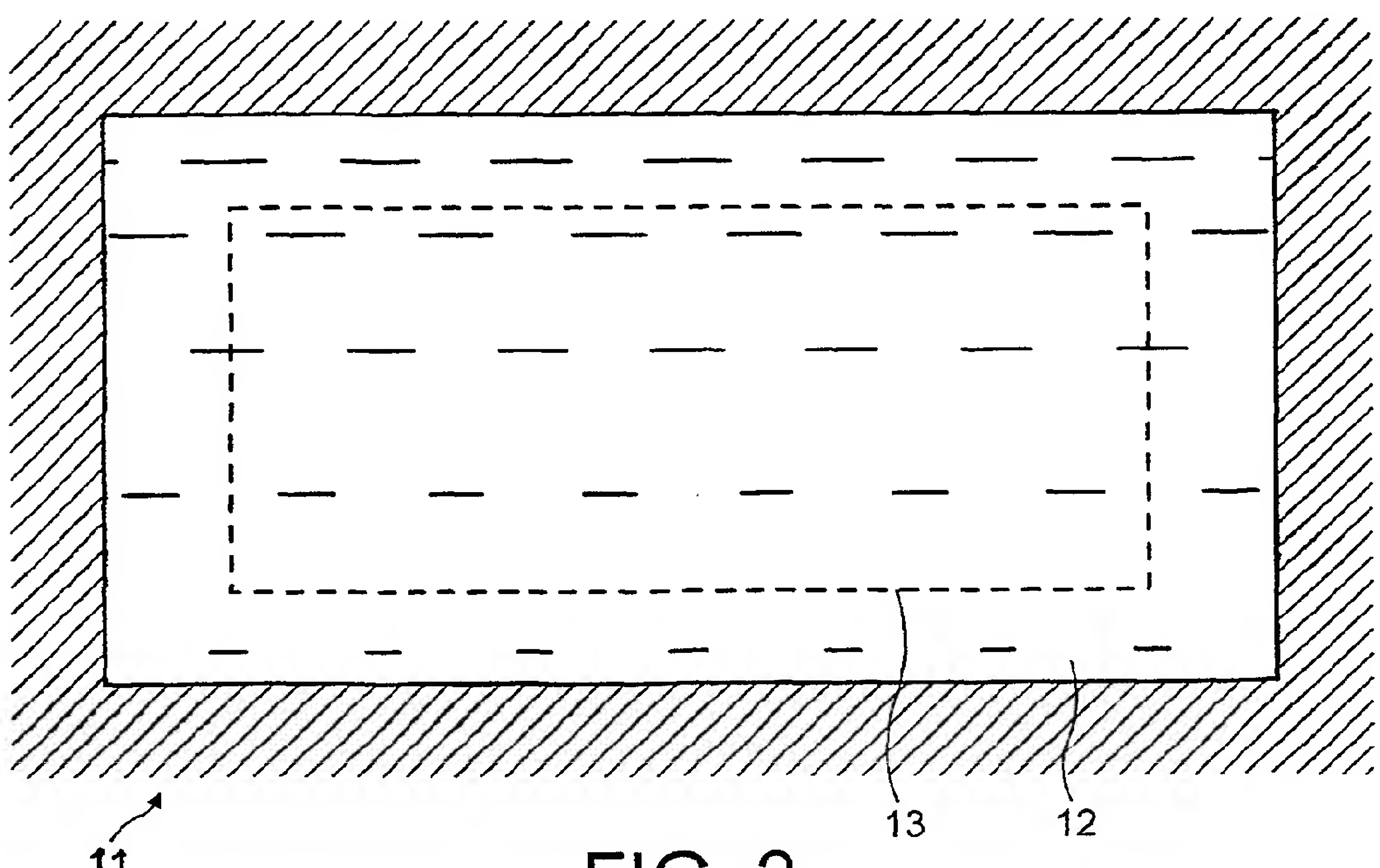



FIG. 2

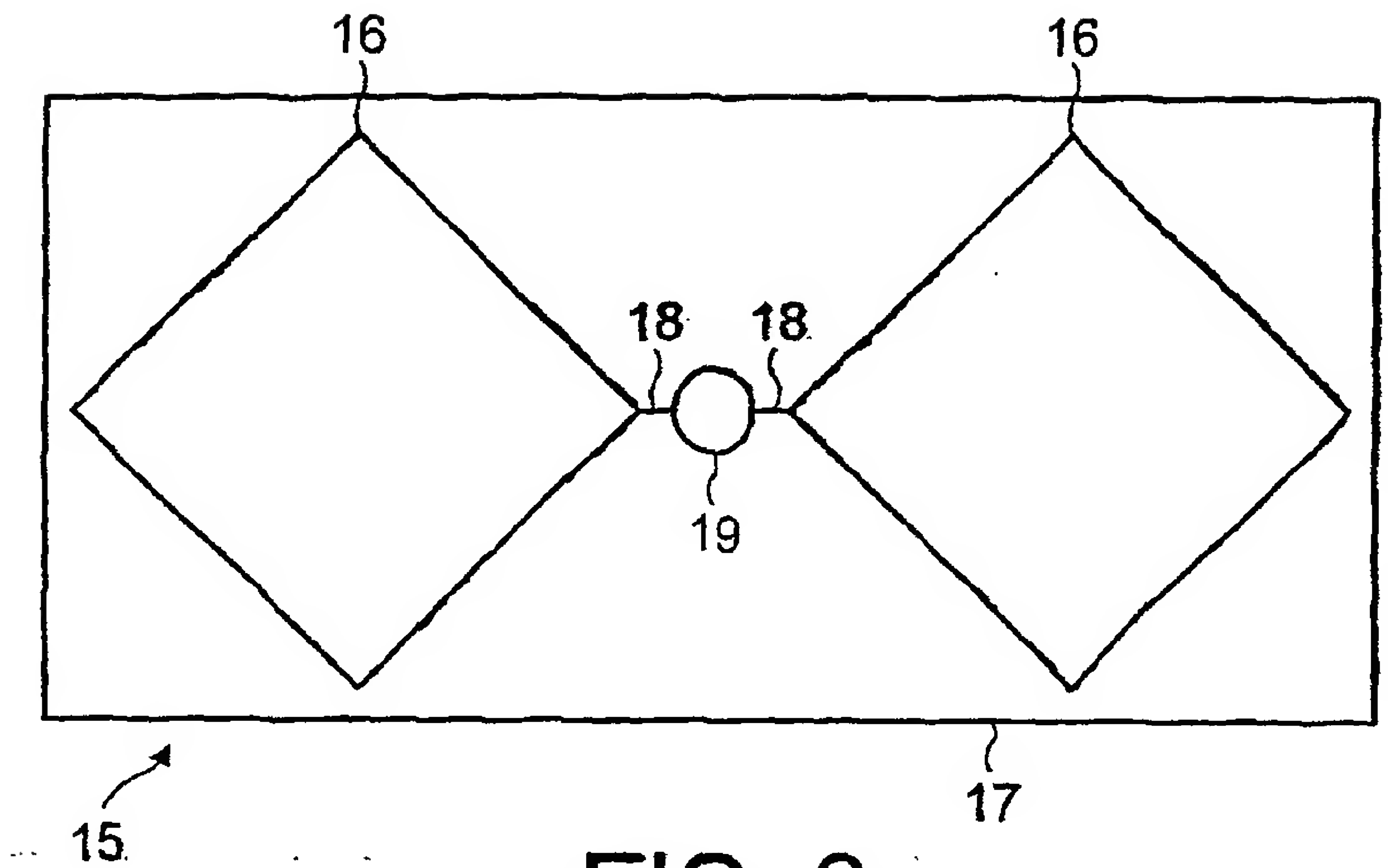



FIG. 3

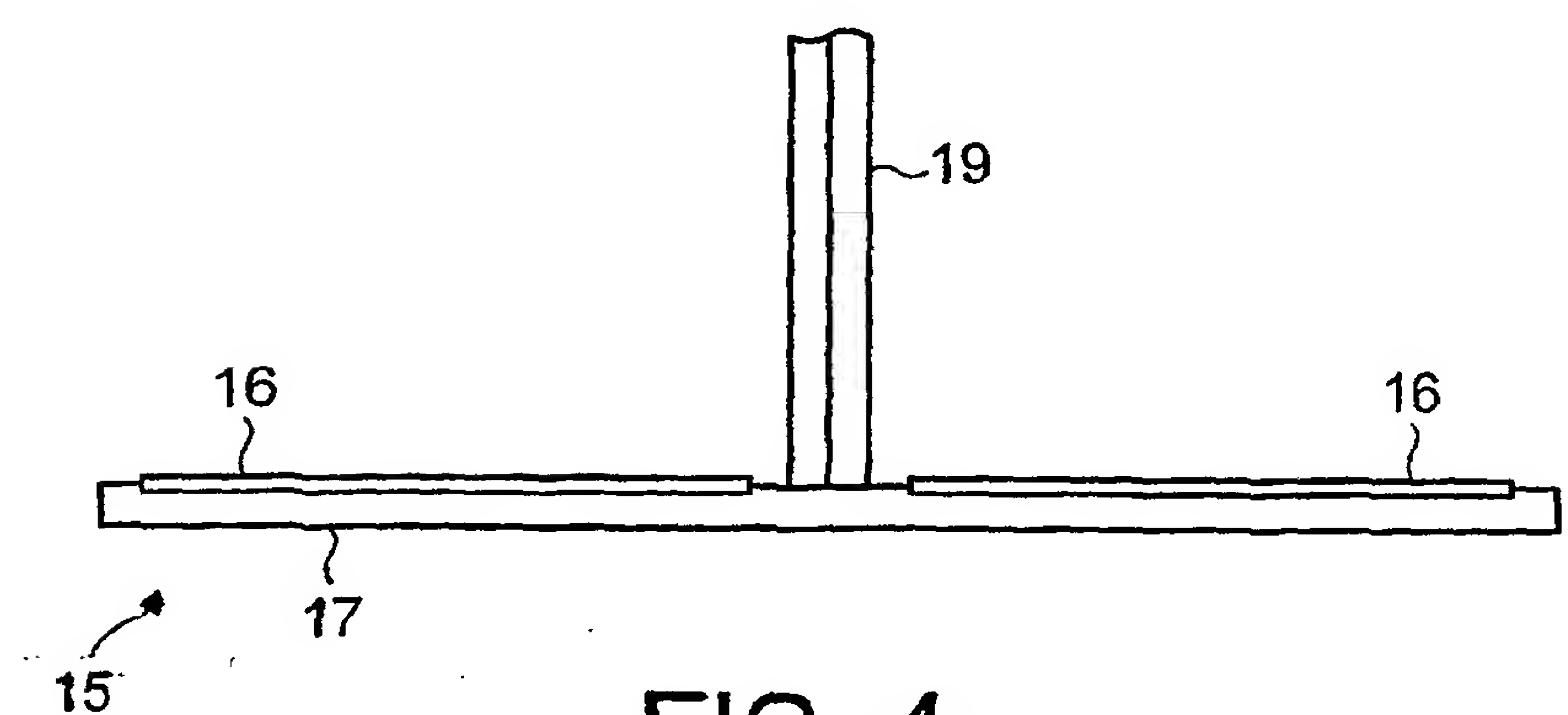



FIG. 4

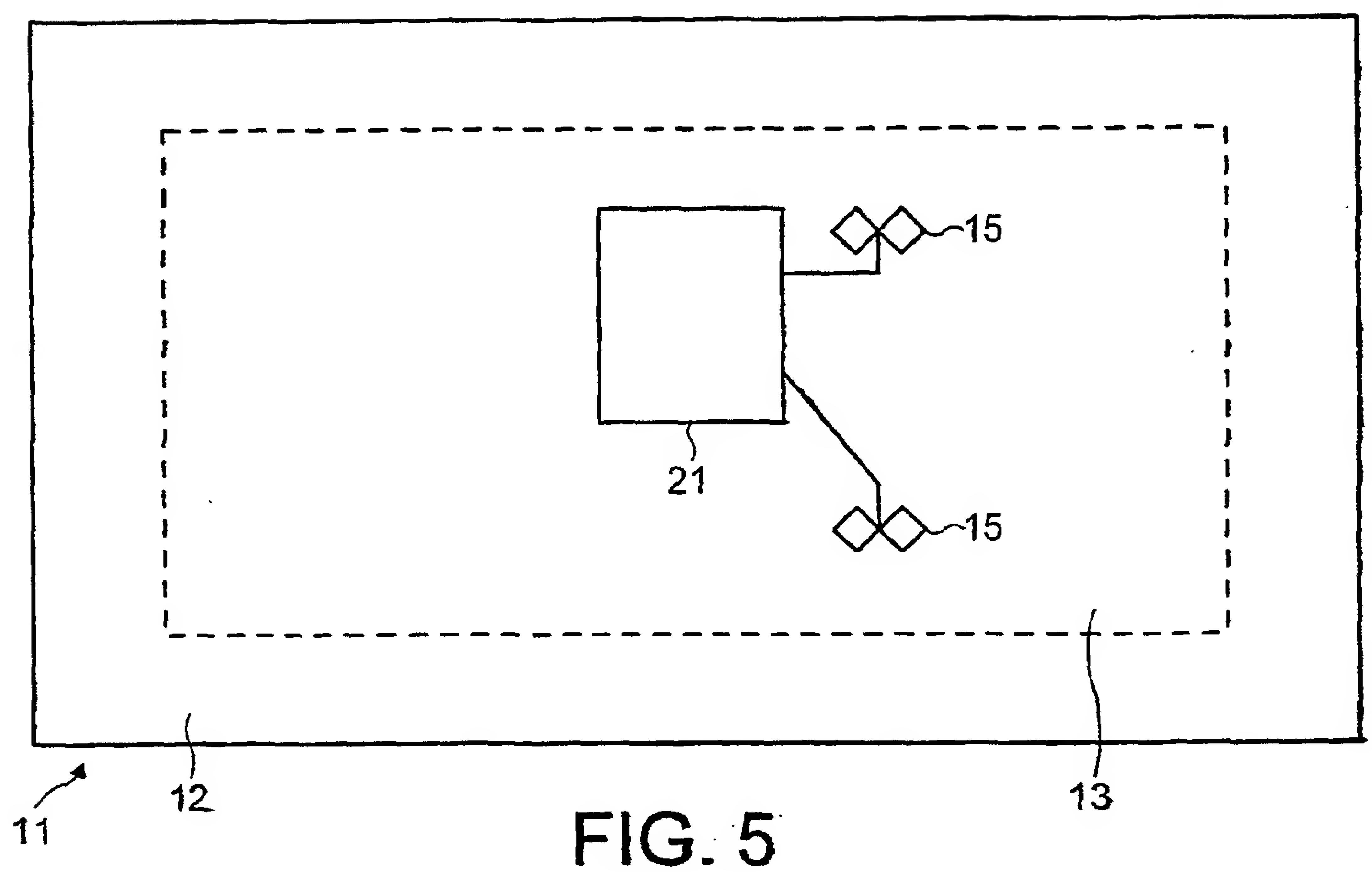



FIG. 5

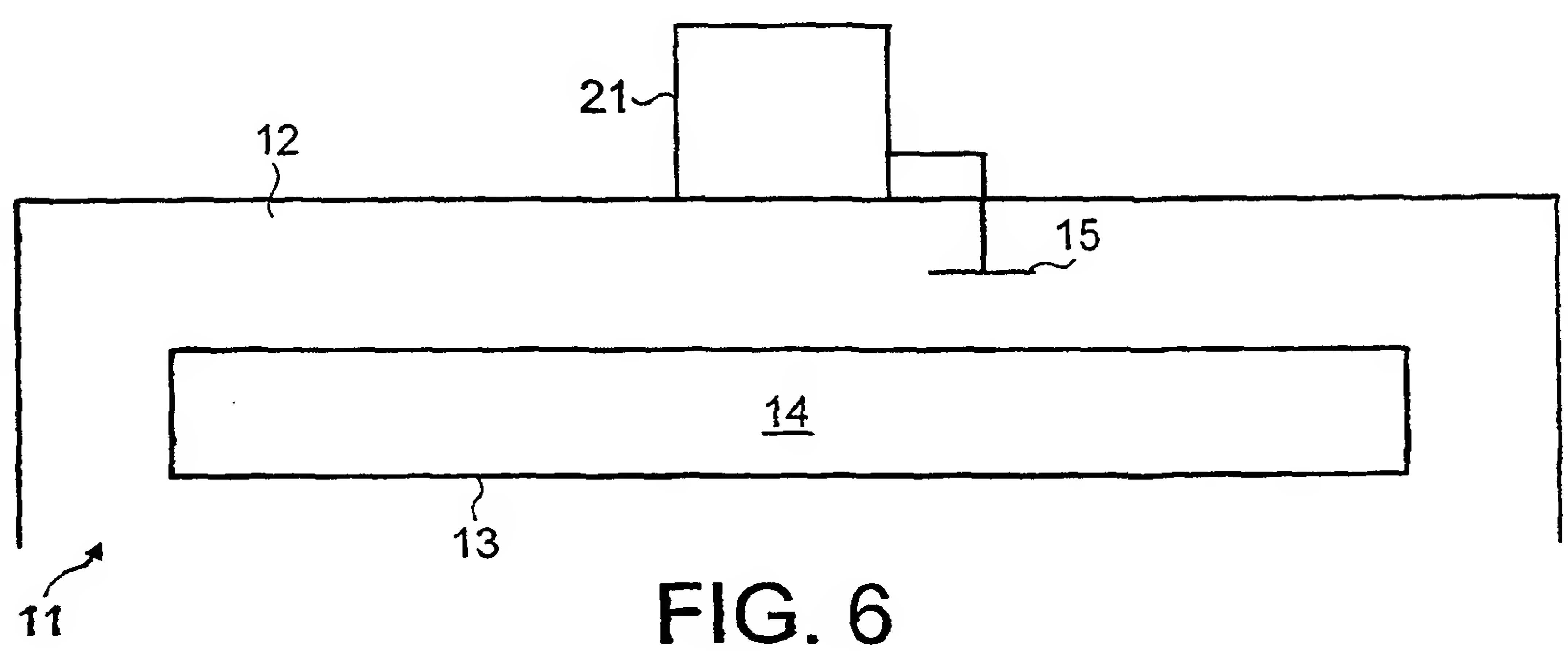



FIG. 6

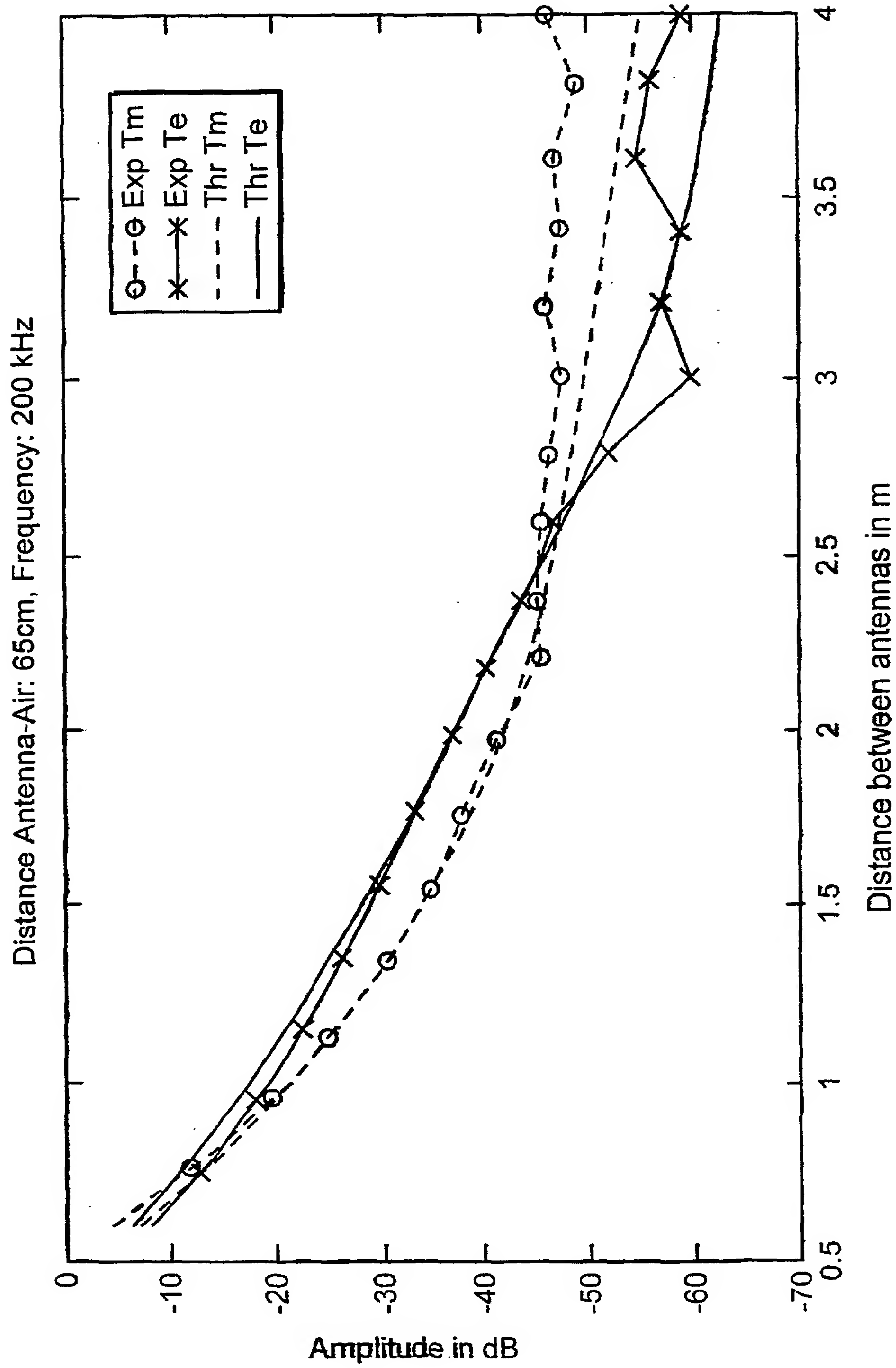
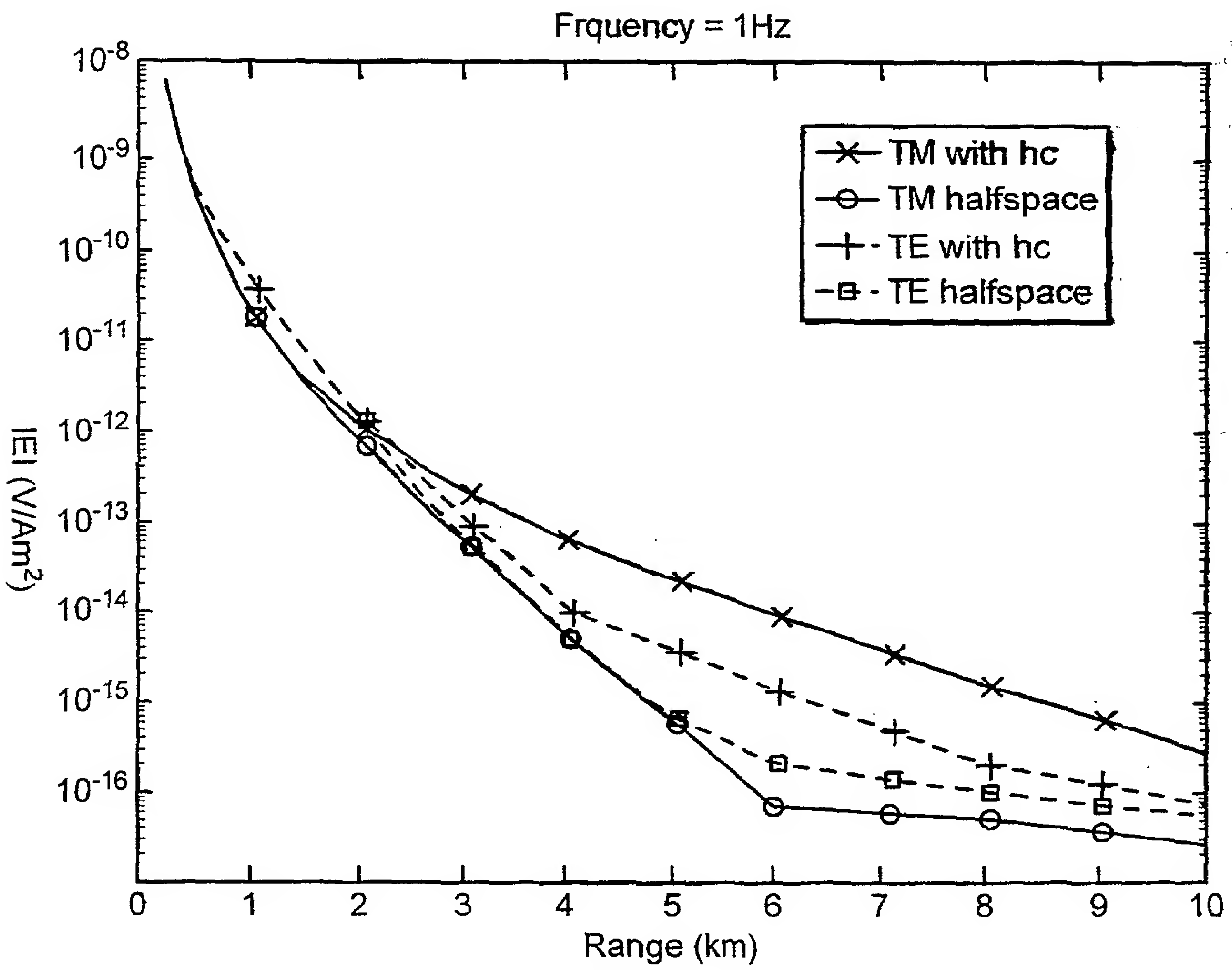

Distance Antenna-Air: 65cm, Frequency: 200 kHz
Exp Tm
Exp Te
Thr Tm
Thr Te
Amplitude in dB
0
-10
-20
-30
-40
-50
-60
-70
0.5
1
1.5
2
2.5
3
3.5
4
Distance between antennas in m

FIG. 7



Frquency = 1Hz
TM with hc
TM halfspace
TE with hc
TE halfspace
|E| (V/Am²)
Range (km)
10-8
10-9
10-10
10-11
10-12
10-13
10-14
10-15
10-16
0
1
2
3
4
5
6
7
8
9
10


FIG. 8

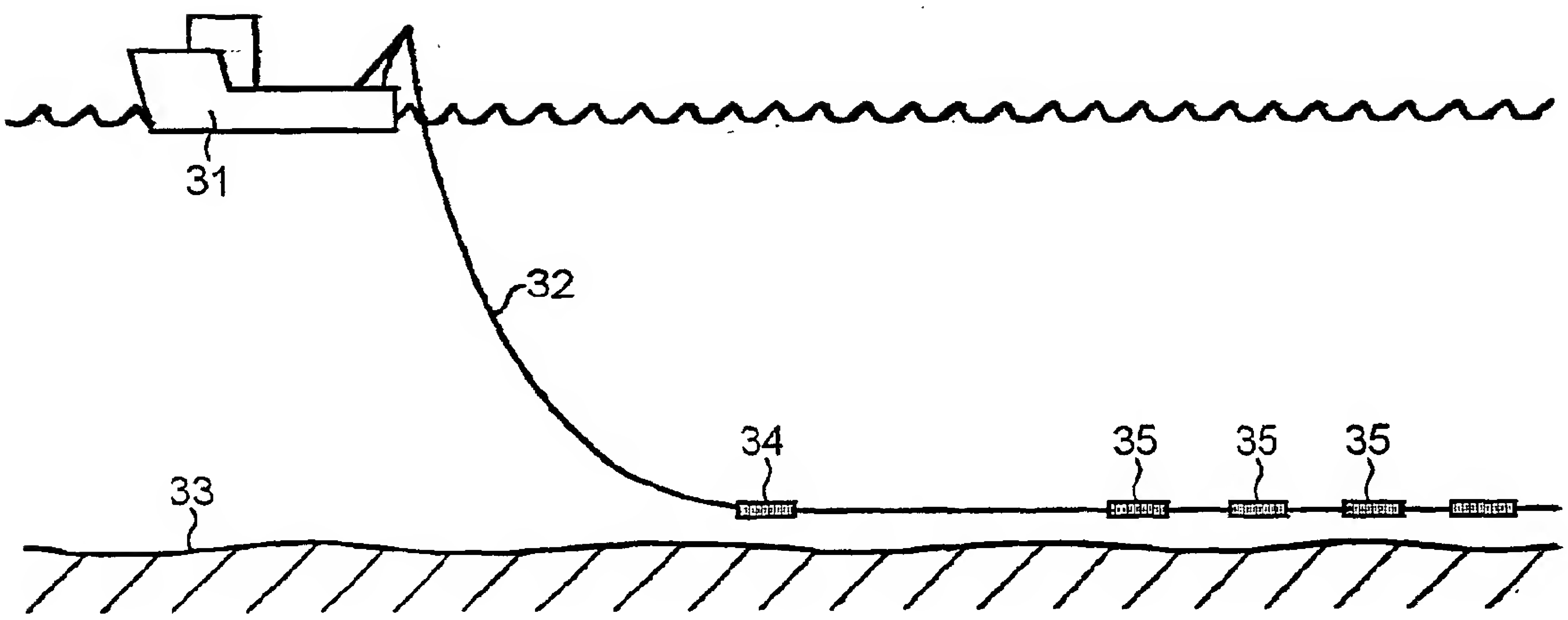



FIG. 9

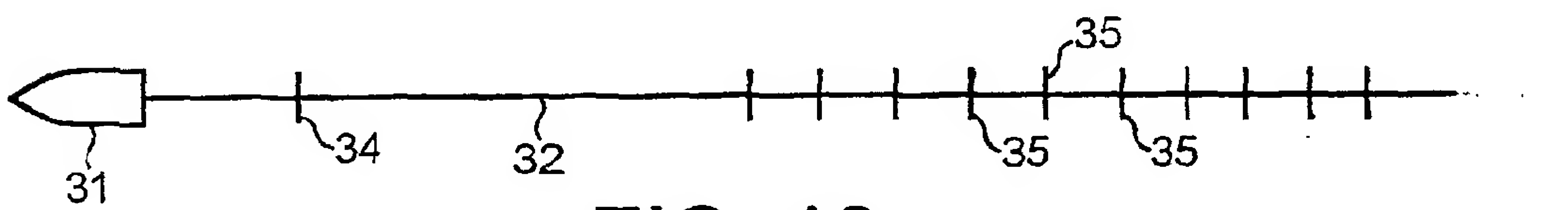



FIG. 10

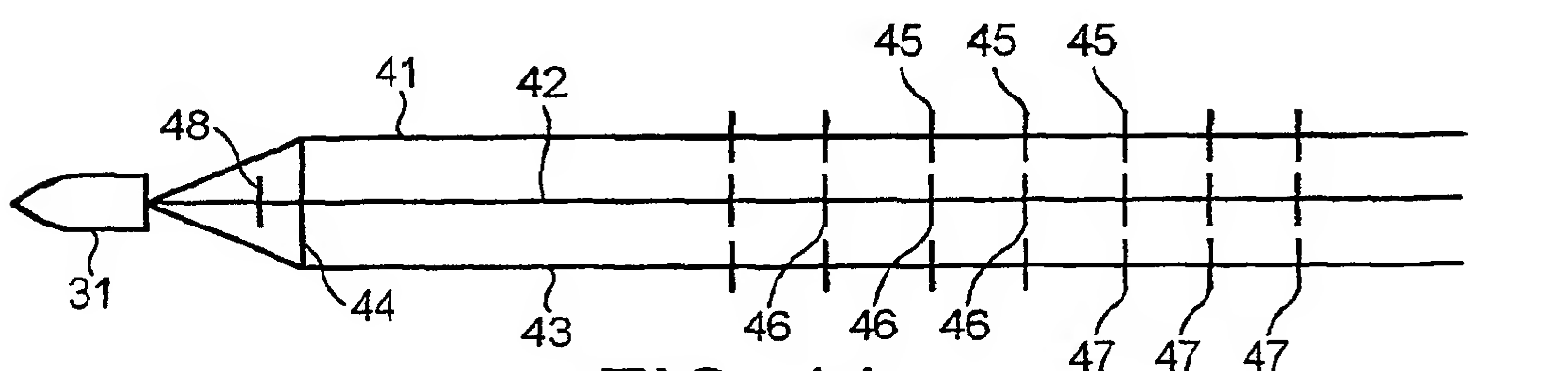



FIG. 11

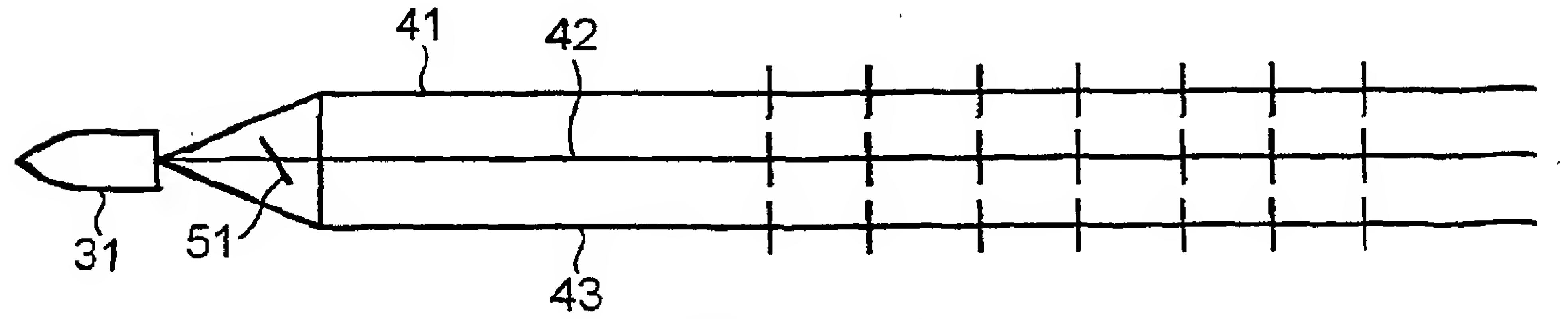



FIG. 12